Psychophysiological Substantiation of the Mode of Piloted Aircraft's Spatial Attitude Information Presentation on a Helmet-Mounted Display in Complex Aircraft's Spatial Altitude Identification and Its Leveling

Moscow, 1998 г

REPORT DOCUMENTATION PAGE

Form Approved OMB No. 0704-0188

1. AGENCY USE ONLY (Leave blank)	2. REPORT DATE	3. REPORT TYPE AND DATES COVERED
	~~22 July 1998~~	Final Report

4. TITLE AND SUBTITLE

Psychophysiological Substantiation of the Mode of Piloted Aircraft's Spatial Attitude Information Presentation on a Helmet-Mounted Display in Complex Aircraft's Spatial Attitude Identification and Its Leveling

5. FUNDING NUMBERS

F6170897W0031

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8. PERFORMING ORGANIZATION REPORT NUMBER

N/A

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

EOARD
PSC 802 BOX 14
FPO 09499-0200

10. SPONSORING/MONITORING AGENCY REPORT NUMBER

SPC 97-4008

11. SUPPLEMENTARY NOTES

12a. DISTRIBUTION/AVAILABILITY STATEMENT

~~No DTIC submission required. Final report was forwarded to~~

12b. DISTRIBUTION CODE

A

13. ABSTRACT (Maximum 200 words)

This report results from a contract tasking Ergocenter as follows: The contractor will
1. Formulate the theoretical concepts of human spatial orientation in flight and psychophysiological principles of helmet mounted display (HMD) design for representation of aircraft spatial attitude position and determine the factors that increase and decrease the efficiency of a HMD as a spatial orientation indicator;
2. Study the psychophysiological particularities of visual perception while using the various versions of a HMD; and
3. Substantiate on a basis of analysis of performed investigations the recommendation on the scope and form of presentation to a flyer the basic information about spatial attitude position of a steered aircraft for HMD visor during unusual attitude recognition and its recovery to flat and level flight.

14. SUBJECT TERMS

Spatial Orientation, helmet-mounted display, cockpit design

15. NUMBER OF PAGES

68

16. PRICE CODE

N/A

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19, SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
UNCLASSIFIED	UNCLASSIFIED	UNCLASSIFIED	UL

NSN 7540-01-280-5500

Standard Form 298 (Rev. 2-89)
Prescribed by ANSI Std. 239-18
298-102

CONTENT

1. INTRODUCTION

The design and creation of helmet-mounted displays (HMD), making possible for pilot to carry out his coverage ability while solving piloting tasks is correctly considered to be a worth-while trend of aviation presentation aids of development. By the type of used components of helmet-mounted displays should be related to electronic presentation aids (PA). Nowadays aircrafts are widely equipped with electronic PA. Many of the developed engineering-psychological problems have a common character and it is reasonable to take into consideration. The results of their investigation when substantiating the standards of HMD information support. Certainly, HMD as a visual indication system has some special features relating first of all to the mobility of an information frame with the reference to information control field of cabin.

The analysis of information encoding in employed and tested electronic PA including HMD, shows that the ways of aircraft's attitude and flight parameters information encoding strongly differ from those adopted on electromechanical instruments. So information about the altitude-speed and navigation parameters is given out not only on usual circular but also on vertical and horizontal scales. Digital counters are also widely used, types of roll and pitch attitude indication are varied, the change of indication scale of one and the same parameter on one and the same scale is applied. All this peculiarities are expedient from point of view of technique, but from the standpoint of human factor they most likely get in the way as their increase the loading on pilot's intellectual and mnemonic functions requiring the reorganization and even development anew of sensor, motor and intellectual components of piloting skill (6, 9).

It's no mere chance that under the development of electronic PA great attention was paid to the idea of analogue to visual flying propaganda. It was considered that displays could present the image (like "way to the sky") of real visual picture which opens up before the pilot directly through the front windshield panel. This idea hasn't been practically established applicated because of technical difficulties and limits and also owing to the fact that flying a modern aircraft requires great capacity of instrument data. In this connection in the exploited electronic PA parameter the ways of aircraft's spatial attitude information encoding are used, but as it was said they differ essentially from the ways habitual to a pilot. When the form and kind of symbols are examined the fact of great variety in flight-navigational parameters presentation attracts our attention. For example, such parameters as speed and altitude might be displayed to flyer on vertical (linear), semicircular or circular scales, digital counter and etc. The diversity of encoding modes appears to be a kind of proof of data for either indication types selection lack. But we should take into consideration that the modes and amount of spatial attitude information encoding must appreciate the main circumstance that HMD is meant for employment first of all in those flight regimes when it is necessary for pilot to acquire at the same time out of cabin visual scene and visual instrumental information.

It should be noted that HMD are introduced in well formed ideology of PA employment and modern and perspective aircraft's design. This fact presupposes a search of optimal strategy of HMD and existing indication systems unification. The experience of electronic displays adoption showed that evolutional approach to new presentation aids introduction on aircraft board is the most optimal. The approach is based on maximum preservation of flight personnel's sensor and motor skills. This could be gained by maintaining of a habitual spatial design of cockpit information field, form and logic of aeronautical and aircraft total form display.

Accounting that informational providing of flying regime is one of the most important HMD functions the problem of rolling display mode selection. This factor exactly can have a decisive meaning in the efficiency of flyer's spatial orientation when complex spatial situation happens during steering an aircraft.. In spite of a long history of studing this problem some reliable and convincing data have been received .iust lately in investigations with immediate comparence between direct and return roll indication on flight instruments, and also in testing the ability of approach visualization in night conditions with the help of prolonged cues (laser beams).

Proceeding from all the above at this stage (of work) it is expediently to examine the following significant and sharp questions, requiring an ingineering-psychological decision:

— the study of aircraft's roll display influence on reliability and efficiency of pilot's spatial orientation at flying the aircraft in complex spatial conditions;

— psychophysiological investigation of peculiarities of simultaneous perception of external visual scene and symbol information on HMD;

— a comparative analysis of the main aeronautical parameters arrangement in visual field and their optimal spatial configuration;

— psychophysiological investigation of various symbol presenting modes of the main aeronautical parameters.

2. Psychophysiological Investigation of Simultaneous External Visual Scene and Symbol Data on the Head-Up Display Perception Peculiarities

The use of semi-transparent HMD reflector allows the pilot to unite instrument information (about flight parameters) and visual external scene in one visual field. Such unification is carried out through optical overlay of HMD collimated image on the out-of-cabin space. In this connection there arises the question of mutual influence of these pitch images and optimal satiation of symbol-alphanumeric HMD data selection which would ensure optimum conditions for instrument aeronautical data perception and search, discovery and identification of ground objects.

To study this question there were carried out some investigations on optical HMD model which made possible the presentation of static informational frames with various symbol-alphanumeric (scales, digital values, symbols) density. The external scene was modeled on the screen set in front of the observer so that HMD visual field and screen dimensions coincided.

Black-and-white photoslides of air observation of different moving ground objects were used as an external visual situation. Average angular size of the object was 40°/min, brightness contrast of object with the background was near 0,2. The exeminee's task was to discover and identificate external background objects and to read the data from the screen of helmet-mounted indicator. The satiation of HMD informational frame with the symbol-alphanumeric information and presence or absence of external visual background played the role of experimental variable quantity in this investigation. Satiation gradations had quantity performance and were determined by the number of discrete elements inthe HMD informational frame. Fig. 1 presents informational frames with various symbol-alphanumeric data satiation.

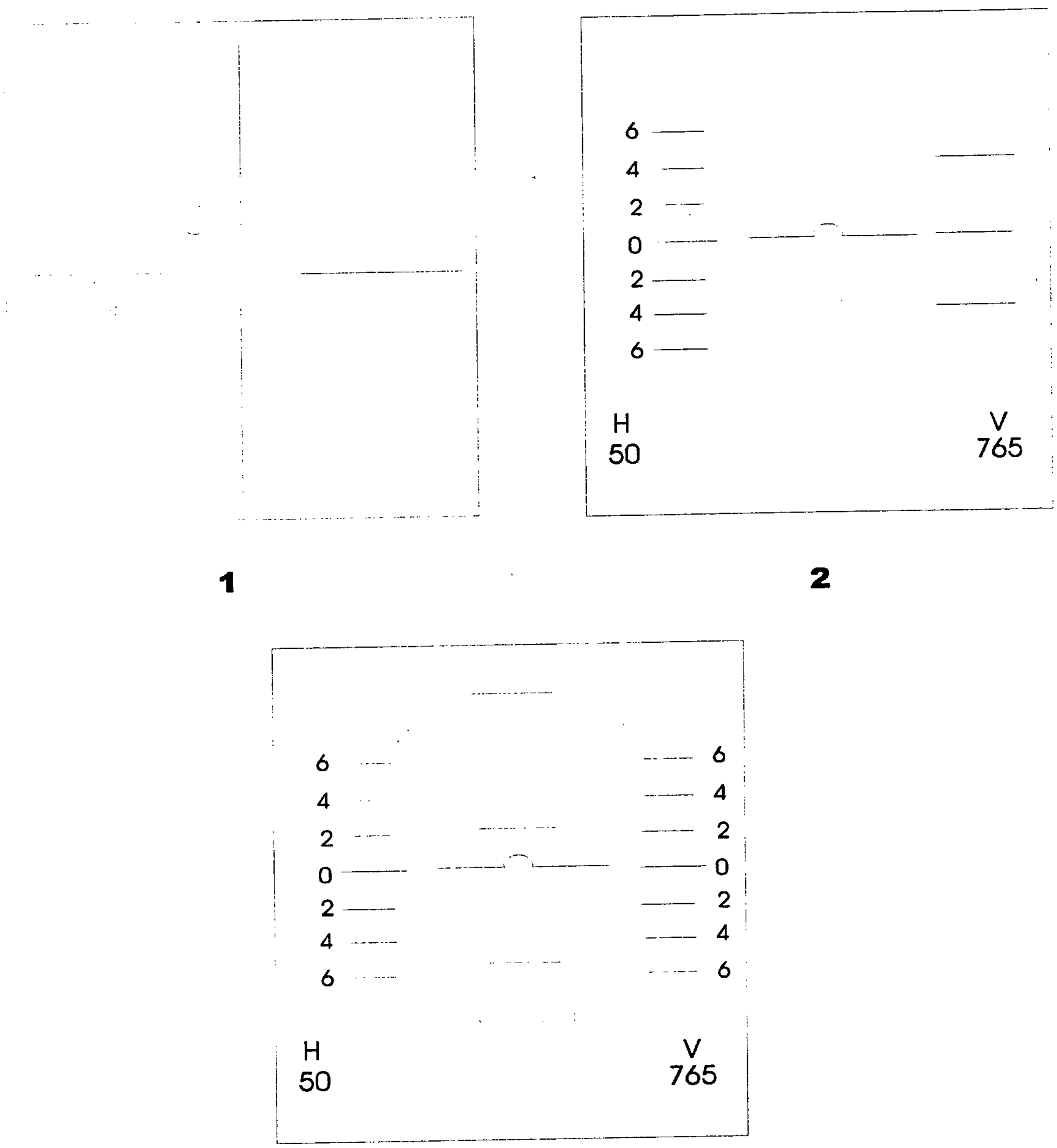

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Fig. 1. The examples of HMD informational frames with various satiationwith symbol-alphanumeric data

1 — informational frame № 1 — quality reading, 5 discrete elements
2 — informational frame № 3 — quantity reading, 25 discrete elements
3 — informational frame № 7 — quantity reading, 44 discrete elements

Scales bars, figures, letters, symbols were treated as discrete elements. Angular dimensions of that elements were: scale bars — 70 arc min, figure and letters — 28×42 arc min, central aircraft symbol — 480 arc min. There were presented 7 informational frames with various symbol-alphanumeric data satiation. It was required of pilot to carry out quality evaluation of index position relatively the scale (on the right, on the left, above and below), on the first and the second informational frames, on the other frames he told quantity values read from the scales. When informational frames were presented on white homogeneous background for quality readout (frames 1,2) their exposure lasted 1 s; for quantity readout (the other frames) — 3 s. When the frames were presented on the visual image background their exposition increased accordingly up to 1,5 and 4,5 s. The preliminary analysis showed that background image (ground cues) was reliably percepted within 0,5 s.

The values of discrete elements number in HMD informational frames are represented in table 1.

Table 1

The number of discrete elements in HMD informational frames

Frame number	1	2	3	4	5	6	7
Reading of values	quality		quantity				
Elements number	5	10	25	30	36	39	44

The reading from the scale with a mistake exceeding the value equal the half of division was considered to be erroneous. Informational frames and slides of out-of-window situation were shown in casual setup. Each HMD informational frame was represented to the examinee 80 times. As evaluation criterion's latent period of voice answer, probability of erroneous scale reading and external situation objects omission were used The results are presented in table 2

Table 2

Indices of reliability of scale reading and indification of external visual background objects with various satiation of symbol-alphanumeric data in HMD screen

HMD informational frame number / Parameters	1	2	3	4	5	6	7
Discrete elements number in the image	5	10	25	30	36	39	44
Latent period (X±m) of scale readout on homogenous white background, s	1,34±0,12	1,36±0,11	1,54±0,12	2,07±0,17	1,81±0,14	1,97±0,16	1,72±0,14
Latent period (X±m) of scale readout on external scene background, s	1,76±0,19	1,65±0,18	2,16±0,23	2,19±0,24	2,14±0,22	2,08±0,22	2,10±0,19
Probability of erroneous scale readout on homogenous white background	0,021	0,022	0,055	0,040	0,053	0,052	0,050
Probability of erroneous scale readout on external scene background	0,055	0,091	0,071	0,080	0,082	0,077	0,081
Probability of ommission of external background objects	0,059	0,071	0,231	0,211	0,312	0,321	0,314

The presented data show that experimental variable quantities — symbol-alphanumeric data satiation in HMD screen and availability of outside visual background — influence not only scale reading accuracy but also objects of external background. The dependence of latent period of scale readout on background performance and discrete elements number in HMD informational frame is represented in fig. 2. Minimum latent period took place on quality data validation (frames 1 and 2) . The execution of quantity reading was accompanied by a reliable rise of latent period, but the number of discrete elements of the picture practically didn't influence this index. The data presented in fig.3 illustrate the dependence of probability of erroneous scale read on background characteristics and discrete elements number in HMD informational frame. On the whole the character of these dependences coincides with the previous dependences, but the external situation background influence is more strongly marked both in quality and in quantity scale reading. To study the influence of discrete elements number in HMD screen on scale data perception a statistic evaluation of these indices with the help of rank correction spiremen coefficient was carried out (table 3).

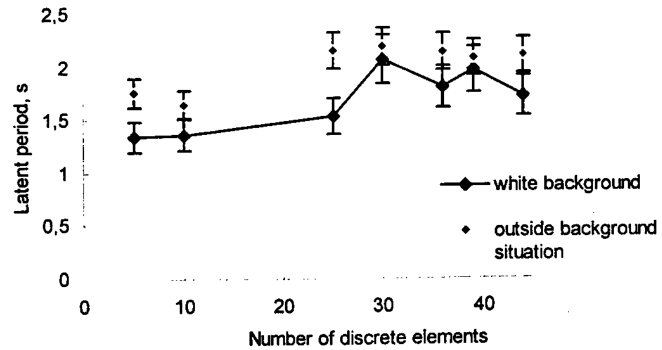


Fig. 2. The dependence of latent period of scale reading on background performance and discrete elements number in HMD informational frame

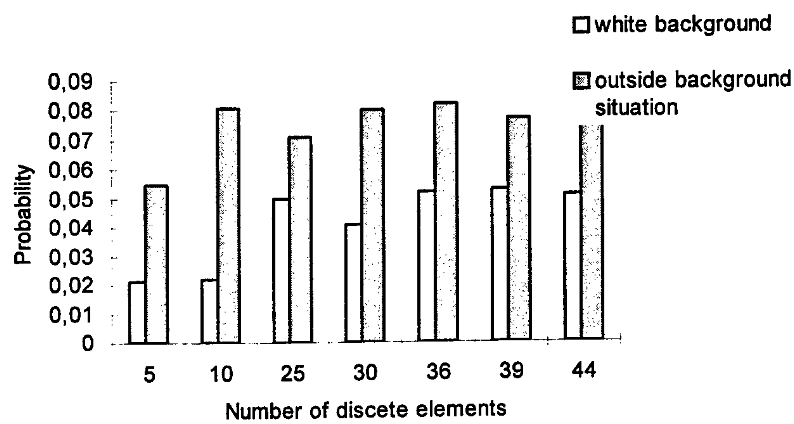


Fig. 3. The dependence of erroneous scale reading probability on background performance and discrete elements number in HMD informational frame

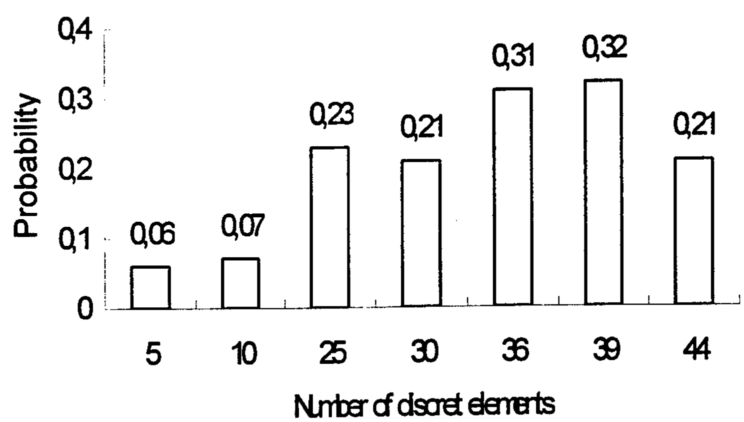


Fig. 4. The dependence of probability of outside background situation omission on discrete elements number in informational frame.

Table 3

The influence of the number of HMD screen discrete elements on scale data perception

Statistic index	Rated Spiremen coefficient	Standard Spiremen coefficient	Influence reliability level
Latent period of scale readout on homogeneous white background	0,69	0,78	invalid
Latent period of scale readout on external image background	0,32	0,78	invalid
Probability of erroneous scale readout on homogeneous white background	0,50	0,78	invalid
Probability of erroneous scale readout on external image background	0,28	0,78	invalid
Probability of omission of external background objects	0,96	0,78	valid p<0,05

On the whole, we may say that in the tested range of values the factor of HMD screen satiation with symbol-alphanumeric information doesn't exert any valid systematic influence on the scale data perceprion. The analysis of the influence of HMD screen satiation on out-of-cabin background cues indentification performed quite different picture. As it may be seen in fig. 4 this dependence doesn't have a linear character: an increase of image discrete elements from 10 to 25 has led to a blunt rise of probability of omission of external background objects analyzed with the help of rank correlation ratio and a valid relation between this indices was found out.

The conducted investigation allows us to give a number of practical recommendations on HMD informational frames optimization. As the test result show visual perception of HMD informational frame and out-of-window situation objects act as rival task.

Proceeding from this it is reasonable to determine the optimal satiation of HMD informational number frame which could ensure maximum probability of external scene identification and reliable fulfillment of flight-navigational task. This task in general view has “min-max” character. Maximum efficiency (time — probability) of outside situation objects visual identification is provided with minimum HMD screen satiation with symbol-alphanumeric information and flight navigational task execution reliability, together with other factors, with indication of the necessary number of the main parameters. The quantity of this aeronautical data depends much on flight conditions: if it is visual or if it is fulfilled beyond the visibility of ground surface and natural horizon line. In the first case the number of displayed parameters may be far less and standards of their presentation format less strict. Besides, HMD frame satiation might be decreased by representing of several parameters in quality state.

So, the analysis of the conducted investigation showed that HMD informational frames development should be carried out by minimization of symbol-alphanumeric information quantity in HMD screen. This may be gained by the use of quality representation of some parameters and the development of several versions of aeronautical frames, which pilot chooses in accordance to flight conditions and tasks.

3. EXPERIMENTAL SUBSTANTIATION OF AERONAUTICAL PARAMETERS IN HMD FRAME DESIGN CHOICE

The question of flight and navigation parameters arrangement in HMD field of view is the most important factor. On the one hand a rational selection of their mutual layout order helps much to reduce gaze shift from one parameter to the other. This will allow to enhance data capacity per time unit, to free the reserves of flyer's attention to carry out some other operations, not concerning piloting and therefore diminish his psychological charge at steering. On the other hand it is desirable to make the layout of the main flight and navigational parameters in HMD field of view and their configuration on the other PA common. This will help to maintain pilot's flying skill and ensure an effective switch from handling with HMD to other PA and the other way round.

The main flight control equipment presenting aircraft's spatial attitude and flight parameters to pilot is: artificial horizon display, horizontal situation indicator, variometer, altitude and speed display. Their layout in flyer's field of view should provide an optimal condition for the parameters perception and on this basis flight image forming, according to which the flyer realizes control actions.

Some of its versions were evaluated to choose an optimal scheme of the main flight parameters layout (1). The validation was carried out on a flight simulator modeling flight dynamics and pilot's seat in a state-of-the-art aircraft. The evaluated versions of the device layout are presented in fig. 5. In the first mode the devices are situated according to the required standards; the second version corresponds to a production aircraft's instruments configuration; the third version is chosen on the basis of algorythm of pilot's activity analysis and account of the basic engineering-psychological principles of panel board design, the peculiarity of the fourth (test) version is a free and unsystemic arrangement of the main flight control equipment.

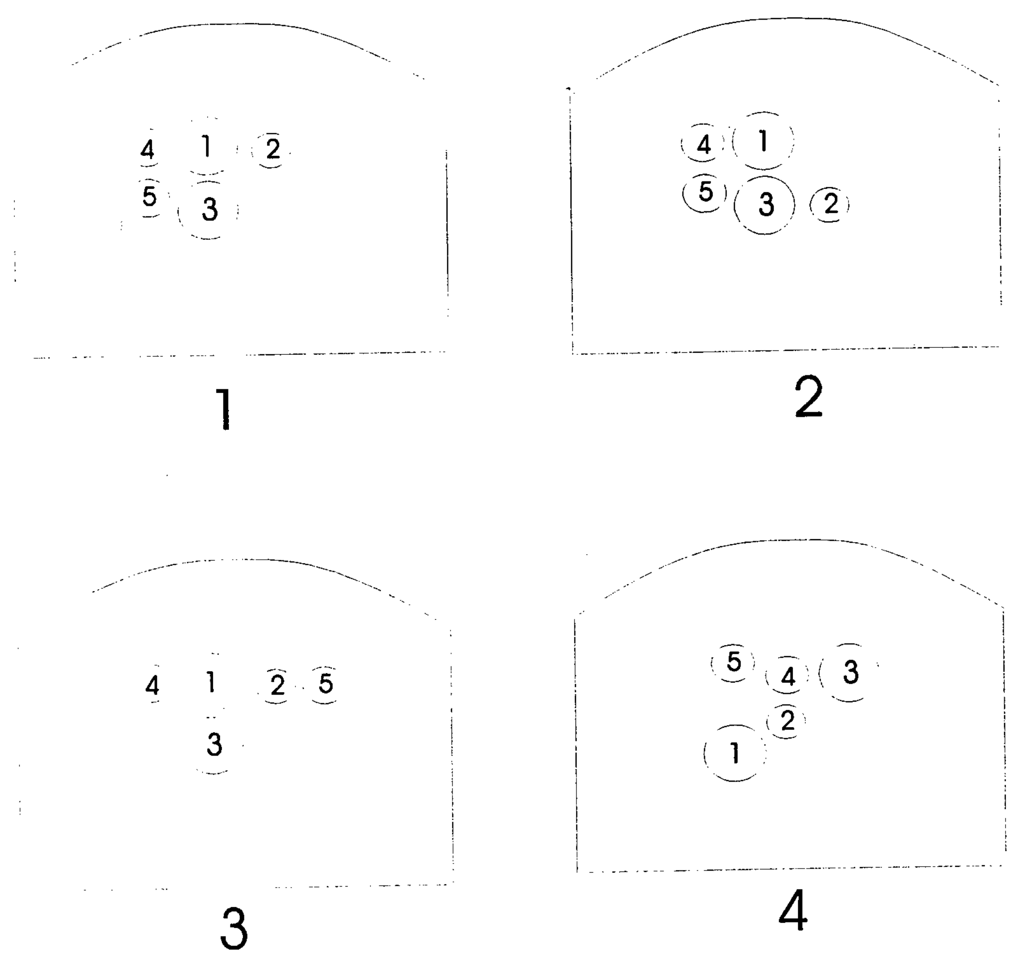


Fig. 5. Evaluated version of flight control equipment layout.
Flight control equipment:
1 — artificial horizon display
2 — variometer
3 — horizontal situation indicator
4 — attitude display
5 — altimeter

The efficiency of pilot's flying activity was evaluated in relation to compared versions by such indices as preset flight parameters maintaining and eye fixation on the devices, discreteness of their data perception, correlation of gaze shift types (horizontal, vertical and in slating directions) eye movements route length. The filming of pilot's line of sight was carried out to study the structure of information getting.

The program of the experiment proposed flying the aircraft using each of the evaluated versions. Piloting task included execution of the following regimes: level flight and banking (γ=30°) at a 500 m height and indicated air speed equal 600 km/h ; ascending spiral with γ=30° roll and vertical speed equal 10 m/s; an approach with the use of radio-technical landing system. Before every flight with a new instrument layout version pilots did their preflight training.

When the accuracy of preset flight parameters maintenance was analyzed it was found out that there were few mistakes in roll maintenance while altitude maintenance errors were characterized by significant variation. As you see in table 4 the third version ensures the best control quality in longitudinal axis. With the second version maximal deflections from preset values of altitude and vertical velocity were observed. This testifies complication of longitudinal channel control. The deflection of control in pitch axis with the second version is more then with the other versions and this fact indicates of control in longitudinal channel complication (table 5).

When version 4 is used during flying the accuracy of holding on the heading has decreased in comparison with the other versions.

The analysis of filming materials registrating pilots' sight directions showed that the frequency of the device use is determined by the significance of its values for control management.

Table 4

Piloting accuracy parameters with various versions of flight control equipment on the panel board layout

Version	Piloting quality parameters — deviation from preset values							
	Altitude				Vertical velocity			
	level flight		360° turn		level flight		360° turn	
	M	σ	M	σ	M	σ	M	σ
1	12,0	7,7	15,1	14,3	2,7	2,0	2,8	2,6
2	15,7	8,8	19,8	15,7	3,9	3,2	4,6	2,9
3	8,9	6,2	13,7	7,3	2,0	1,4	2,6	1,8
4	13,8	7,9	21,6	13,1	3,6	2,1	3,7	2,8

Table 5

Characteristics of motor activity and getting when the main flightcontrol equipment is differently arranged

Version	Characteristics of motor activity — deflection of controls in pitch axis during the approach, deg		Characteristics of information getting correlation of scan types, %			
			Correlation of scan types, %			Gaze shift route length,m/min
	M	σ	horizontally	vertically	in slanting directions	
1	4,7	2,9	61,8	21,1	17,1	14,2
2	7,4	3,6	31,4	20,3	48,3	15,4
3	3,5	2,1	77,3	17,6	5,1	12,5
4	4,3	3,1	6,3	10,7	8,3	15,1

Table 6

The relative number of gaze shift (in % to the total) in dependence on the main flying instrument layout

Version	Gaze shift route						
	AH — Var	AH — HSI	AH — altitude display	Var — altitude display	Var — HSI	AH — V	Others
1	42,0	14,2	11,1	12,5	2,4	5,3	12,5
2	27,0	18,0	14,6	11,3	12,3	7,9	8,9
3	44.1	18,6	2,0	21,0	2,4	6,0	5,9
4	57,7	1,8	6,9	12,6	0	12,7	8,3

Table 6 shows that at any version of device arrangement the greatest number of gaze shift is between artificial horizon (AH) and variometer (Var). The necessity of frequent handling of this instruments is caused by the fact that their reading are used to adjust the flight control actions. At the same time data collection characteristics depend also on steering with the version 2 the number of eye movements between AH and Var significantly lowered, discreteness of Var data perception increased and became 1,5-2 times as much. The position of altimeter near variometer (version 3) led to increase of the number of eye movements between them. When AH and horizontal situation indicator (HSI)are spatially remote (version 4) the number of eye movements between them lowered while the discreteness of HSI perception increased (3-5 times as much depending on the flight regime).

The comparison between the routes of gaze shifts on the devices showed that the maximum number (77%) of horizontal gaze shifts takes place with version 3; in other layout versions the significant part fell on inclined and vertical movements. It is common knowledge (2) that horizontal gaze shifts are the most physiological ones, causing minimum weariness. This is probably related to a prolonged experience elaborated in reading texts.

The length of gaze shift routes during instrumental data collection is an important criterion of optimum device arrangement. The shortest gaze shift route pertime unit appears at steering with the third version of the device layout. When the other configurations are used the route becomes 14-23 % longer. Considering the gaze shift speed to be approximately the same in all cases we may say that the use of version 3 for other things being equal can ensure the rise of attention reserves paid to the above-mentioned values.So, the realized investigation surely shows the preference of the third version of flight instrument layout.

You see in the given figure this preserves the direct of the main deviceslayout.

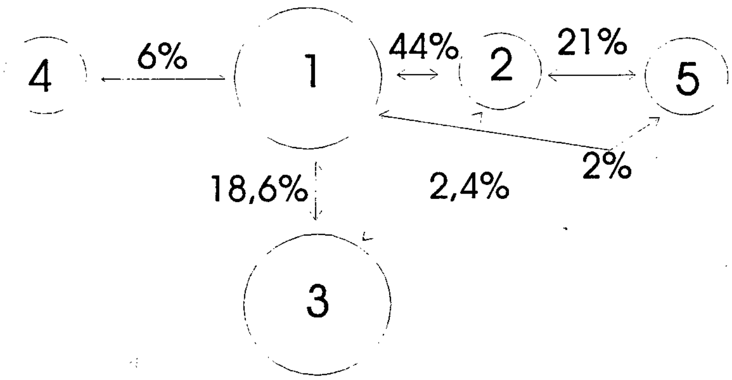


Fig. 6. Distribution of pilot's gaze shift route at steering with the optimum flight instrument layout version
1 — artificial horizon
2 — variometer
3 — horizon situation indicator
4 — speed display
5 — altimeter

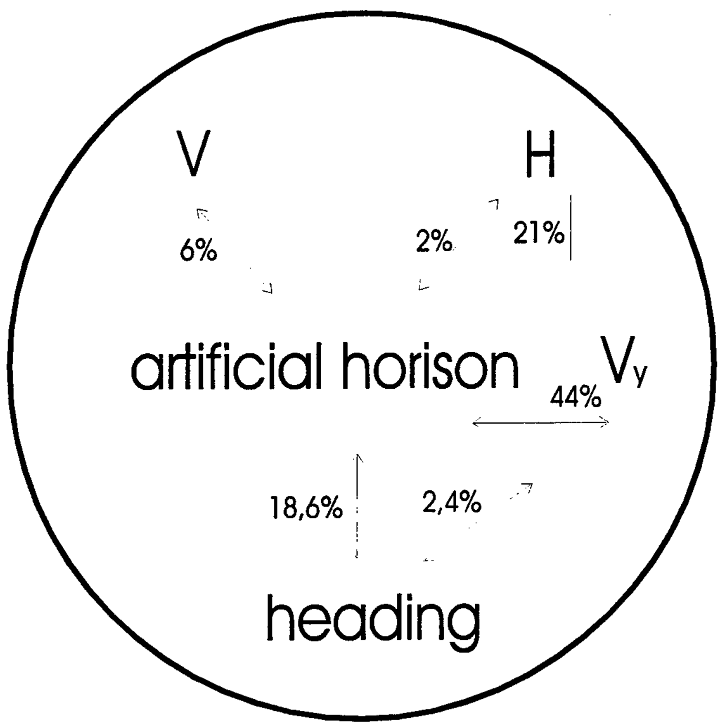


Fig. 7. Configuration of the main flight parameters in HMD informational frame.

The given scheme of the main flight devices configuration is taken as a basis of flight frame formation on the displays of Russian aircrews. So, its maintenance is reasonable when forming a flight informational frame. But the direct layout transfer to the instrumental frame is difficult by force of number reasons. In this connection when HMD informational frame was formed the task to preserve the closest functional connections and optimal (vertical and horizontal) routes of pilot's gaze shifts about the HMD frame had been settled. In fig. 6 the routes and the frequency of flyer's gaze shifts (the data available from table 6) at steering with the optimal configuration variant (version 3). With layout in question 91,6% of scan route is accomplished in vertical and horizontal directions. The fact that when moving from an artificial horizon to an altimeter the gaze route crosses a variometer could be reffered to symbolic defects of such configuration. On the basis of realized analysis the flight parameters layout in HMD informational frame is suggested (fig. 7). Taking into consideration real visual fields of modern helmet-mounted displays the layout is completed in reference to a circular with the diameter of 30 arc deg. As you see in the given figure this design preserves the direct field of views proximity of the main devicesand and ensures in 83,6% of cases a shift of pilot's gaze in horiontal and vertical directions.

4. Psycophysiological Substantiation of Flight Data Representation Form in HMD Screen for Providing the Identification Aircraft's Complex Spartial Attitudes and Its Recovery to Level Flight

The form of flight information presentation is one of the main factors ensuring effective aircraft flying and reliable pilot's spatial orientation. A spatial place in this problem is occupied by the question of spatial orientation with the help of aircraft's roll display. Relating to this it is reasonable to begin the consideration of flight data indication problem with substantiation aircraft's roll display mode.

4.1. Psychophysiological Substantiation of Aircraft's Roll Display Mode

The mode of spatial attitude display is called to ensure the conditions for improvement pilot's in-flight spatial orientation reliability beyond the visual scene of natural horizon line, for its rapid recovery. As biological system of human spatial orientation in three-dimensional environment is adapted only to earth surface gravitational conditions, the occurring in flight due to unusual physical inertial effects on human and other "visible field" disturbances of sensory signals synthesis, on a base of which the mental presentation of spatial position, is formed, lead to occurrence of erroneous estimation of its spatial orientation. In visual flight the suppression of negative effects of such disturbances deploys without participation of cognitive sphere owe to prevailing role of stable visual image of space, developed in process of flight training. The most important premise for spatial orientation maintenance beyond the limits of terrain visibility — is the conscious reflection by flyer the controversy of coming up signals, their intellectual estimation. It is just biological inability of human to spatial orientation out of ground visibility has challenged the urgent need in development of technical devices for indication of spatial attitude positions (artificial horizons), which enable to compensate such deficiency. There are two main types of spatial attitude indicators. In the first one the movable relatively longitudinal axis (that is on roll) aircraft symbol is presented. The horizon line is moved relatively trainsversal axis of aircraft up and down, in parallel with this axis. Such mode of aircraft's spatial attitude representations called outside-in". On the device of second type the horizon line is moved relatively fixed aircraft's transversal axis, which goes not only in up and down directions, but also inclines to the right (at left banking) or the left (at right banking). Such indication is usually named as inside-out". Such mode of spatial attitude display is characterized as "direct or "natural", basing on the fact, that pilot sees such visual scene of earth surface as moving or shifting space. In other words, on indicator is copied the unusual sensual tissue of perceptive image, the attempts of visualize the "blind" flight were undertaken to ensure the external similarity between visual scenes, viewed by pilot in visual flight rules (VFR) and instrument flight rules (IFR) conditions.

Concept of expediency for such mode of indication as analogue of visual panorama, which flyer views out of cockpit , was advanced in the USA. The author of this idea is US Navy aviation surgeon J.Poppen. The idea looks so natural that even Poppen himself ignored to site some substantiation of its correctness. One of the causes of vitality of such concept consists in what, that people of non-flying professions, including the engineer-designers of flight display systems, being in flight, percept the terrain and horizon perceptive as moving cues. Therefore, they strive to represent on facial part of attitude indicator the moving horizon line by analogy with natural horizon. But can such mode of spatial attitude information display be considered visualization of flight? Certainly, no. the efficient mode of spatial attitude visualization, which might be effective, should be built in such way, that it could "trigger" the whole set of psychic reflection mechanisms, which are involved in VFR conditions. Artificial aviation horizon display of any type of spatial attitude indication mode compulsory presupposes the mental transformation performance of instrumental signals. Henceforth, no one form or mode of indication of aircraft's spatial attitude position, can not warrant an absolutely reliable determination of its aerial situation, especially in complicated flying situations. The question contains in that, what type of indication is easier to yield to decoding? The simpler and the more rapid is mental transformation of flight display instrument information, the more probable is the surmounting of aberration in spatial presentation image, the more is reliability of flyer's spatial orientation.

Comparative investigations of efficiency of two main types of aviation artificial horizon attitude indicators, used by flyers, have been conducted from the early 30-ies (8-10, 12-14). The analysis of the above cited research works allows to conclude, that not with standing their controversial data, related to experimental conditions (real flight, simulator tests) and specific traits of facial forms of spatial attitude indicators, most of researchers are stressing the advantages and preferences for ″outside-in" indication type. But such conclusion did not have practical effects. In most countries, including US, for some decades the flyers are steering and main training the required spatial attitude control of aircraft on indicator with movable horizon line. In Russia the prevailing type of spatial attitude indicator is ″outside-in", but approximately 15 years ago importunate attempts to replace them by opposite type "inside-out" began and in some aircraft types these unjustified changes were succeeded. As leading arguments the keen supporters of such replacement used and cited the foreign aviation indication ″inside-out" more realistically approaches the flight visualization. However, many foreign flyers and engineering psychologists pose the question about deficiencies — from the viewpoint of human factor — of inside-out mode of spatial indication in piloted aircraft.

Proceeding from the all aforesaid, for the good of psychological grounding in selection of spatial attitude indication mode, we have carried out a set of experimental researches, which were aimed to determine pilot's conceptual model content, study of its interaction with spatial attitude information model and evaluation of interconnection of flyer's efficiency and reliability actions with specific traits of this interaction .

The first series was aimed at revelation of content specificity in flyer's conceptual model and its influence on efficiency and reliability of human spatial orientation in flight. Two groups of examines took part in this experiments: flyers and operators without flying experience. The experiments were carried out in real flights on laser guidance landing system (2). The task of the test - subjects was determination of aircraft's spatial position on a landing flight - path approach after artificially evoked spatial disorientation. The examinee, for some predetermined time interval was deprived the possibility to get flight information, hence the consecutive apparition of monitored and perceived by him aircraft's position was sudden for him. According to experimental procedure the examinee was seated in right flight chair (second pilot's seat).

Experimenter (flyer in command or commanding flying officer) changed spatial attitude position of piloted aircraft, after he had deprived test subject from viewing the flight regimen parameters. At that time there had been emerged the deviations from present flying approach trajectory and correspondingly had changed mutual position of laser beams.

At the command of experimenter the test-subject was to estimate spatial attitude of piloted aircraft relatively demanded heading and glideslope flight path, to determine the roll of aircraft and to report on an aerial situation. Besides this, in some flights the tested flyers were not only to report, but take control of aircraft in command and put it into set landing approach flight-path. The aircraft was equipped with flight recorders, which enabled to get all the necessary output data, that is: temporal characteristics of flyer's activity, content of oral replies, quality of maintaining the flight regimen, flyer's line of sight.

Let us appeal to the received data. First of all, the fact, that flyers didn't make any mistakes while the operators have admitted considerable number of erroneous judgments (41,3% errors in spatial attitude estimation) has drawn our attention. It is very characteristic, that the errors in determination of direction deviations in roll axis prevailed (Table 7).

Table 7.

Number and character of errors, made by operators

Type of error	Gist of error	Number of errors, %
I	In determination of localizer and glideslope position in presence of roll	9,7
II	A. In direction of roll B. In direction of deviations on heading C. In direction of deviations on glideslope	18,4 2,6 10,6

Latent time of spatial orientation recovery (by oral responses) in flyers was much shorter ($p<0,05$), (fig. 8).

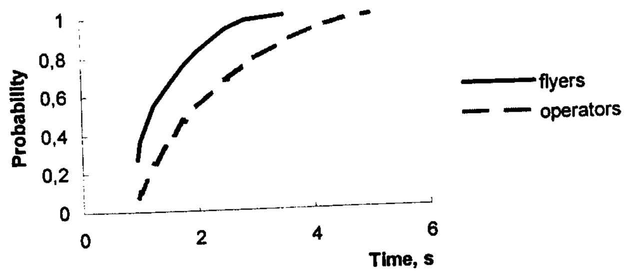


Fig.8. Distribution function of latent period of inflight estimation of attitude of piloted aircraft

According to their subjective accounts, the operators had difficulties in determination of aircraft's spatial attitude position. Incidentally they perceived and interpreted the beams as moving in reference with themselves: "When flyer has leveled from roll, I have felt it as a rapid shift of heading beam and quite the other position relatively to landing strip direction, though in fact heading did not change at all" (Operator K.); "The glideslope beam petals were very mobile, as pointers-symbols" (Operator B.). As to flyers, their perception of beams in flight was principally different from operator's one: they perceived the beams as extended in space ground cues, fixed, as an earth itself.

The data about dissimilarities of characteristics of flyers' and operators' actions, received in experiments, are determined by difference of internal content in actions, directed to evaluation of spatial attitude position. It means, that in flyers and non-flyers there are functioning two different in its content images of spatial attitude position perceptiveness. In operators there has been noted full coincidence of mental representation with visually perceived picture. In flyers the spatial relationships are transformed and represented in geocentric co-ordinate system. Such transformation, adaptation to changed sensual matter of image (visible field) occurs as he advances in flying experience and spatial orientation perception in flyer adequately corresponds to his awareness, that is, he himself is moving in reference with earth, but not earth in reference with him. It is precisely the flying experience and skill (conceptual model) of participating in flight experiments flyers, which allowed them in contradistinction to operators to evaluate their position in space without errors.

In the experiments of the second series there was compared efficiency of flyer's actions, while using spatial attitude indicators of various types. The experiments were conducted on-board of flying laboratory, in cockpit of which were alternately mounted the indicators with type of roll indication "outside-in" (indicator A.) and indicators of type "inside-out" (indicators B and C) - see fig. 9. The indicators B and C were diapered in presentation of facial layouts.

The dual-control aircraft was equipped by blinding hood, which could close completely the out-of-cabin forward canopy view together with flight display instrument panel, the recording device (cinematographic camera for flyer's eye-movement activity monitoring in first forward-cabin, magnetic flight recorders for control of flying parameters and operations of flyer, tape recorder and physiologic data registering device). In order to establish the specific relationships in steering control and spatial orientation on compared spatial attitude indicators the experimental design has provided: a) performance of simple and complicated elements in aerobatics manoeuvring under blinding hood (such approach simulated the instrument conditions beyond the visibility of ground cues); b) sudden transition from VFR conditions to IFR - conditions (there were modeled such situations in flight activity, when during piloting the flyer unexpectedly met "the clouds", there were evaluated the peculiarities and efficiency of transition from direct immediate spatial orienting to mediated with use of compared indicators one); c) introduction to tested flyer of complicated spatial attitude situations (simulation of spatial orientation loss with partial or full failure in mental presentation of spatial attitude position: such model allowed to determine the time and reliability of flyer's recovery from unintelligible spatial attitude situations in relation to compared indicators). Before instrument flights the flyers had passed training on special ground simulator which allows to practice their flight task. In postflight period the flyers were questioned about specific features of IFR conditions. As criteria in evaluation of flyer's performance quality and interaction with compared spatial attitude indicators were used: a) the precision characteristics of flight control parameters' maintenance; b) the specific features of visual attention sharing; c) the gist and total number of erroneous actions of flyer during maneuvering and recovery from complicated spatial attitude situations; d) temporal characteristics of flying activity in incomprehensible flight situations; e) subjective evaluations by flyers themselves the comfortability of steering control on a base of 5 point scale.

A. B. C.

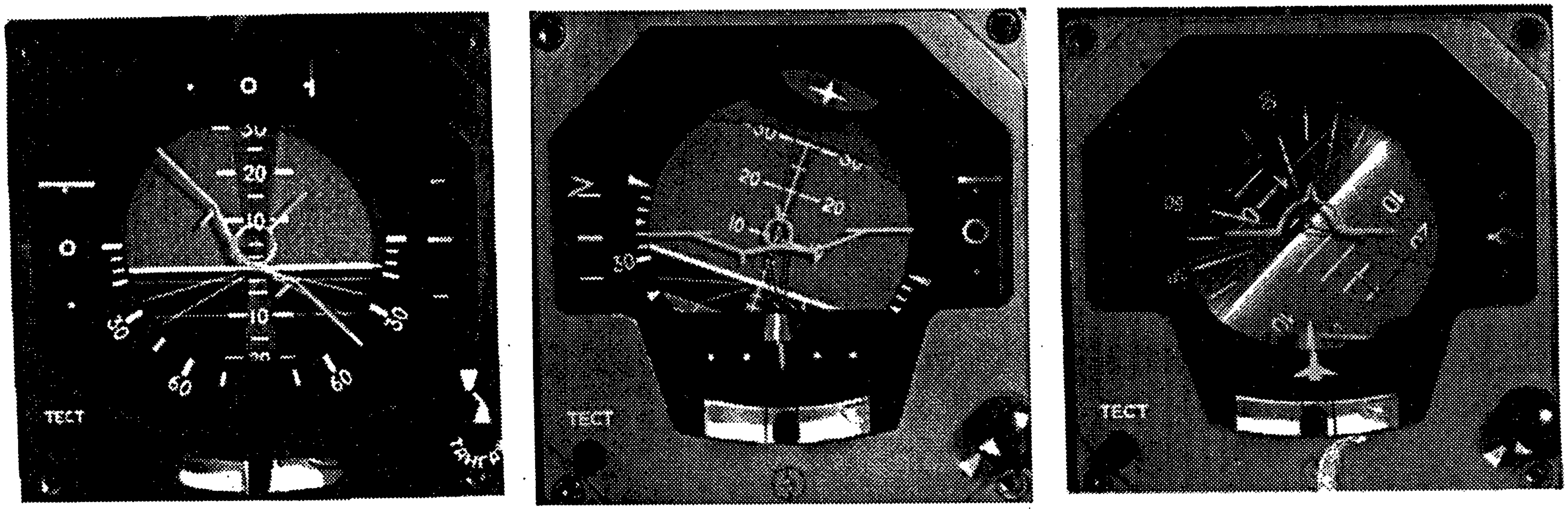


Fig. 9. Facial parts of attitude indicators
A — type of indication “outside-in”
B, C — type of indication “inside-out”

Analysis of flight performance indices on the compared indicators has revealed significantly greater accuracy in maintaining of set flight parameters in roll and pitch angles in fulfillment of complicated spatial maneuvers (for example, oblique half-loop, half-roll and split S, multiple 360° rolls with fixation of pre-set point of banking, spiral), using "outside-in" spatial attitude indication mode (Table 8).

Table 8

Performance efficiency of slanting loop and half-roll as juged in control points

Type of spatial attitude indicator (artificial horizon)	Appraisable indices			
	Value of roll deviation, deg		Value of pitch deviation, deg	
	M	σ	M	σ
A. “Outside-in”, moving plane	4.2	7,2	5,8	7,1
B. “Inside-out”, moving horizon line	9.4	8,7	10,2	11,0
C. ΠInside-out”, moving horizon line	11.3	8,9	17,1	12,9

Using a spatial indicator of type "outside-in", the flyers also had allocated their visual attention in more rationally, in contrast to maneuvering in aerobatics evolutions with visual control on an indicator of type "inside- out", where their visual activity was accompanied by concentration of their attention on facial part of the indicator owing to this the reduction of time fixations for flight parameters controls significant for flying safety. Finally, debriefed flyers gave a more higher appreciation to spatial attitude indicator "outside-in" from the view point of handling comfortability and efficiency in comparison to its counter-part "inside-out" display. The analysis of spatial attitude image formation conditions at use of "inside-out" indicator has shown, that in this case there are required from flyer to rehearse some additional mental efforts on transformation of apprehensible on the indicator banking position picture into representation of rolling in geocentric co-ordinate system. In other words, the flyers have perceived on the indicator a fixed aircraft symbol and mobile sphere and encrypted both into representation about position of moving aircraft in reference with motionless earth. Embarrassments in data transformation especially marked were at roll angles, exceeding 45', pitch angles, going beyond 20' and high angular velocities (more than 30'/s) of aircraft rotation in space. As an index of such difficulties served the trial and search control stick movements in lateral steering channel for avoidance of deviations from pre-set banking angle (30% of cases) during transition of flyer from visual flight to IFR conditions. Therefore, the flyers in some cases deliberately have narrowed the field of visual attention, consentrating on the display, reaching in such way an illusory perception of fixed aircraft symbol movement. At employment of "outside-in" spatial attitude indicator the spatial representations have been worked out much easier and simpler, because the spatial relationships between elements of information display field were presented in geocentric co-ordinate system, that is, in a system, which flyer applies invisual flight. Characteristics of flyer's actions throughout the recovery of aircraft from complicated (after partial loss of orientation) spatial attitude situation (fig. 10).

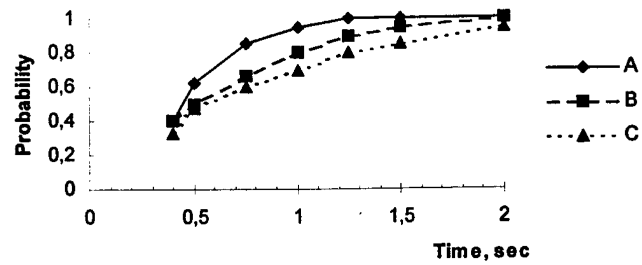


Figure 10. Time of spatial attitude position evaluation and number of errors
A — with indicator of type “outside-in”
B, C — with indicator of type “inside-out”

First of all, there is noted significantly greater total number of fallacious actions, related to incorrect spatial attitude judgement of aircraft, when one compares the indication "inside-out" type with "outside-in" type.

The difficulties, experienced by flyers in perception and treatment of spatial attitude information at use of " inside-out" indication type, are further being affirmed in prolonged eye fixation time on spatial set indicator after removal of the hood from flight instrument panel. For example, duration of first eye fixation on "outside-in” indicator in 96% of cases did not exceed 1,0 s, while at evaluation of aircraft’s spatial attitude on "inside-out" indicator more extended time duration limits (up to 5,2 s) dominated. At last, during recovery of aircraft from complicated spatial attitude position, while using "inside-out" display, there are insufficiently precise controlled very important from the viewpoint of flying safety flight parameters. This had led especially to significantly greater loss of altitude ($p<0,05$) . In general, the results of experimental investigations of second series have revealed a clear advantage of "outside-in" indicator in comparison with indicators of "inside-out" type. It encompasses not only the indices of efficiency and awareness of flyer's activities during steering, but also the characteristics of their reliability in a conditions of spatial disorientation. Undoubtedly, the quality of external design of facial part in spatial attitude indicator (painting, dimentions, form of indeces etc.) plays some important, but not decisive, role. At the same high level of facial part design layout in compared indicators the advantages of presentation from corresponding to inner content of spatial attitude image, which was formed in flyers, were manifested .

The third series of investigations was endeavored to disclose the peculiarities of pilot's spatial orientation, while handling the aircraft on head-up displey (HUD) in dependence on the type of used artificial horizon presentation. Since HUD is designated not so much for proper flying in clouds, as for conditions of ground visibility and natural horizon, as well as in conditions of frequent alternation of orientation models, so far the adept adherents of "inside-out" spatial attitude indication type insist, that in collimator display should be compulsory represented the indication with moving horizon line, coinciding with the line of natural or visible horizon. Otherwise, they suppose, the errors will be unavoidable, especially in transition from instrument flight orientation to visual one. Relying on theoretical views about content and functioning of flight image, we consider such opinion as erroneous. It was necessary to refute or confirm such viewpoint in flying experiments. The initial flights with HUD were performed in visual meteorological conditions. The spatial attitude indicator on roll in HUD was of "inside-out" type, while on instrument panel there was "outside- in" indicator type. Very interesting facts were received. As it became clear after flights, the flyers even did not recognize, that on HUD the direct type of spatial attitude indication was realized. Incidentally, nobody did notice any difficulties in flying due to different types of spatial attitude indications: the flyers in all cases have perceived the motion of aircraft in reference with ground surface. The explanation is that in good visibility of natural horizon conditions, the flyer himself orients on ground-heaven horizon cues, so the form of spatial attitude indication in HUD is of no significance. But in IFR conditions, especially during dense clouding penetration, they experienced very noticeable difficulties, while referencing the "inside-out" spatial attitude indication, because they interpreted the HUD artificial horizon moving line for the motion of steered by them aircraft. There were registered up to 20% fallacious control stick movements. However, when on HUD was mounted the spatial attitude indicator of "outside-in" type, no difficulties in spatial attitude position estimation and no erroneous control stick motions have been evolved at all.

According to this findings pilots themselves came to a strongly simplistic conclusion: for them as initial cue and reference point to read rolling of aircraft always serves the horizon line itself (natural in visual flight and artificial in IFR conditions). Flyer never controls the horizon line, because such action is unnatural to him. Therefore, perceiving, from the one hand, the natural horizon and rotation of aircraft's nosecone in reference with it, and, from the other hand, rotation of aircraft's symbol on HUD relatively to artificial horizon line, the flyer does not experience any difficulties in judgement of spatial attitude position of piloted aircraft.

Summing up the received data, let us try in generalized form to adduce the reasons in favor of spatial attitude "outside-in" indication type:

1. Modern theoretical concepts about spatial orientation relationships, mechanisms of psychic regulation of flyer's activity, results of carried out by us experimental investigations, of the influence of correlation between information model of flight and flyer's conceptual model on mental content of his operative image and reliability of spatial orientation, allow us to conclude about the necessity of accordance of aircraft's spatial attitude representation on indicator to flyer's psychic image of flight. The flight image is in its gist a geocentric one, that is in it are reflected the ground and immobile horizon. So, if imply the enhancement of spatial orientation reliability in flight beyond the visibility of ground cues, the used means of indication must guarantee the formation of image, reflecting the spatial relationships in geocentric co-ordinate system.

2. The presentation of external out-of-cabin space view on indicator is not visualization on flight. Moreover, in perception of such indicator the mechanism of adaptation, consisting of suppression by geocentric conceptual model of space of unusual sensual matter of comprehension (moving visible field), fails and flyer can not apprehend the picture moving on indicator as immobile, as he identifies the ground and its cues in visual flight. Hence, the spatial attitude indication principle must conform not to visible environment which shifts relatively to aircraft cockpit, but to flyer's image which reflects the stability of horizon.

3. The display of any information presentation type surely presupposes the mental transformations of instrumental signals. Application of indicator, built-up on the principle "inside-out"

complicates cognitive activity, entangles the cycle of psychic actions owe to additional mental transfiguration of perceived rolling image into concept about rolling in geocentric coordinate system. The use of spatial attitude indication type "outside-in" does not require these additional exertions. The image of moving aircraft symbol on indicator concurs with image concept, elaborated in flyer (the essence of his conceptual model).

4. The technical realization of aircraft's spatial attitude presentation of "inside-out" type in any aesthetic fulfillment is psychologically defective. Perspective of development of spatial attitude indication presentation in future flying vehicles will be determined by creation of flight visualizators, warranting the identity of three-dimensional space presentation metrics to real out-of-cabin viewed space.

4.2. Investigations of Psychophysiological Peculiarities of Pilot's Activity When Fight Parameters are Indicated on Different Types of Scales

Formation of HMD informational frame presupposes it's filling with flight control information in the form identical to pilot's mental concept model, and optimal for it's visual perception and building of control actions.

The main feature complicating the task of informational frames formation is necessity of presenting a significant number of flight parameters with the help of minimum symbol-alphanumeric elements. The decision of this problem should have two ways: choosing optimal scale performance and integrated flight dect design requiring only quality monitoring.

General rules of data perception from different types of scales are studied well enough (3, 5, 10), but in the greater part of researches evaluation of either type of scale was carried out by criterion of quality and quantity indeces reading efficiency (time and correctness). Proceeding from this in the chapter in question variants of scales, general rules of their reading will be briefly examined, but main attention will be paid to experimental study of flyers activity at steering with use of different types of scales.

In special series of experiments the influence of some peculiarities of HMD flight information encoding on pilots' steering activity were studied.

The aim of the first series of experiments was to compare two ways of flight data presentation by means of moving vertical scales and immovable scales with moving reference cursor.

There was studied an efficiency and psychophysiological structure of pilot's actions at handling a simulator with HMD on which vertical velocity information was presented on a mobile scale with an immovable reference index or vice versa immovable scale with a mobile reference index. As you see in table 9, flying with HMD movable rate indicator led to an increase of dispersion.

Table 9

Comparison between dispersions (conv. units) of controls deflections in longitudinal channel when the two types of scales are used

Scale type	Flight regime			
	level flight	360° turn	spiral	approach to land
immovable	2,3	3,3	3,2	3,1
moving	4,1	4.0	4,9	4,0

Hand motor characteristics of EMG amplitude values at steering a simulator with the use of compared types of scales are presented in table 10.

Table 10

Bioelectric activity of a forearm flexor in dependence of scale type (overage amplitude, mcV)

Scale type	Flight regime			
	level flight	360° turn	spiral	approach to land
immovable	81,5	94,9	97,1	106,0
moving	94,5	103,2	113,1	125,2

The analysis of muscles bioelectric activity shows reliable ($p<0,05$) increase of amplitude while using moving scale. The rise of gaze fixation duration 1,5 times as much on moving scale in comparance with immobile one also indicates the impediments in maintaining vertical velocity values.

On a basis of received data we may affirm that information displayed on moving scales doesn't ensure any conditions for functioning of prognozing mechanisms which adjust motor activity. Incidentally, the algorythm of moving activity is broken.

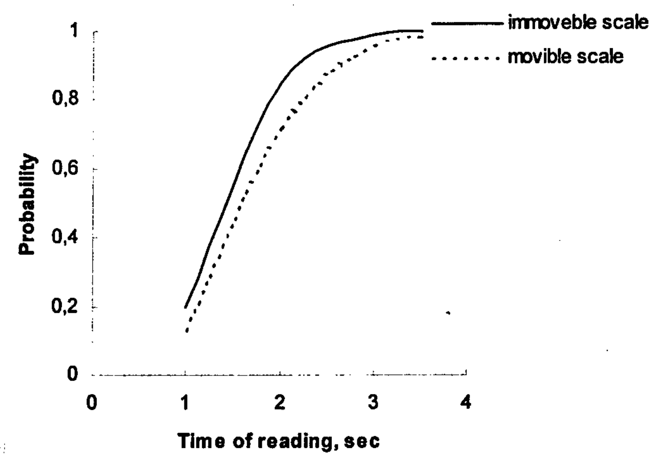


Figure 12.

Distribution functions of the compared scales reading time.

The fact that there are no quality distinctionsin data reading between the compared scale types out of the dynamics of a perceived signal corroborates the correctness of this supposition.

When some flight parameters (including rate speed) are displayed it is necessary to indicate a large range of values, this leads to inadmissible increase of linear size of scales. Way out of this situation could be found with the help of dial scale change in certain moments.

The second series of experiments carried out on laboratory simulator studied the influence of dial scale change on their reading characteristics. The two identically designed variometer vertical scales differed in division (5 m/s and 25 m/s).
This scales are presented in fig. 13.

A produced probability of a scale with a 5 m/s division was 0,75, of the other — 0,25. The analysis of the results revealed some difficulties in evaluation of variometer with 25 m/s division reading. This difficulties were manifested in increase of read out period and errors (table 11).

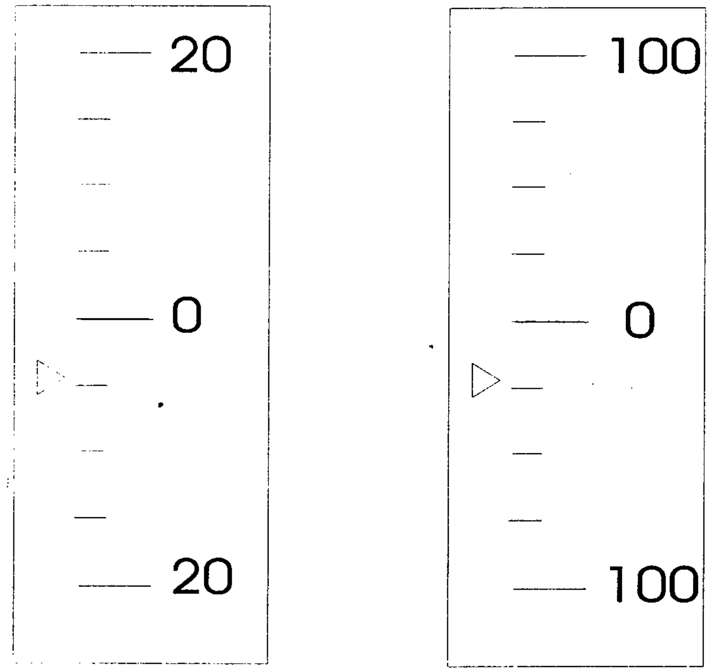


Fig. 13 A schematic picture of facial parts of variometers
A — division 5 m/s
B — division 25 m/s

Table 11.
Characteristics of readout from variometer dials with various scale

Scale type	Readout time, s M±m	Errors concerning the change of scales,%
Variometer with 5 m/s division	1,82±0,66	—
Variometer with 25 m/s division	2,42±0,81	9,0

The most typical were such errors when the parameters marked with a bar were read correctly while the values between bars in the scale of the first dial. For example, an examinee evaluated a speed of 30 m/s on a scale with 25 m/s division as if it was 27 m/s, and 45 m/s — as 48 m/s and so on. Obviously, a subjective scale image model which is used by a test subject corresponds to a scale with 5 m/s division (as more often presented one) in such mode every position of moving readout cursor is related to a strictly definite rate parameter. A discrepancy between model-image and object image when at presenting a scale with 25 m/s division caused some difficulties in its reading.

Subjective accounts studing showed that when scales are changed an examinee carries out information re-encoding. It is natural that this operation leads to reading period extension and doesn't exclude some errors.

So, a change of scale especially after prolonged use of the other dot scale exerts negative influence on pilot's activity efficiency.

Proceeding from the negative result of series of experiment in question an attempt of variometer scale development with appreciation of specification of its use on different flight regimes was undertaken. There was conducted a form interrogation of flight personnel which aimed was to determine a necessary accuracy of variometer data readout on various flight regimes. The results of this questionnaire has shown that flight personnel prefers to use a traditional semicircular scale to indicate rate parameters. The most precocious speed readout (up to 1 m/s) is required at landing with parameters range of ±5 m/s. At level flight maintaining reading exactness could be of 1-2 m/s. In up to 15-20 m/s rate range it is desirable to ensure possibility of displayed parameter change pace determination.

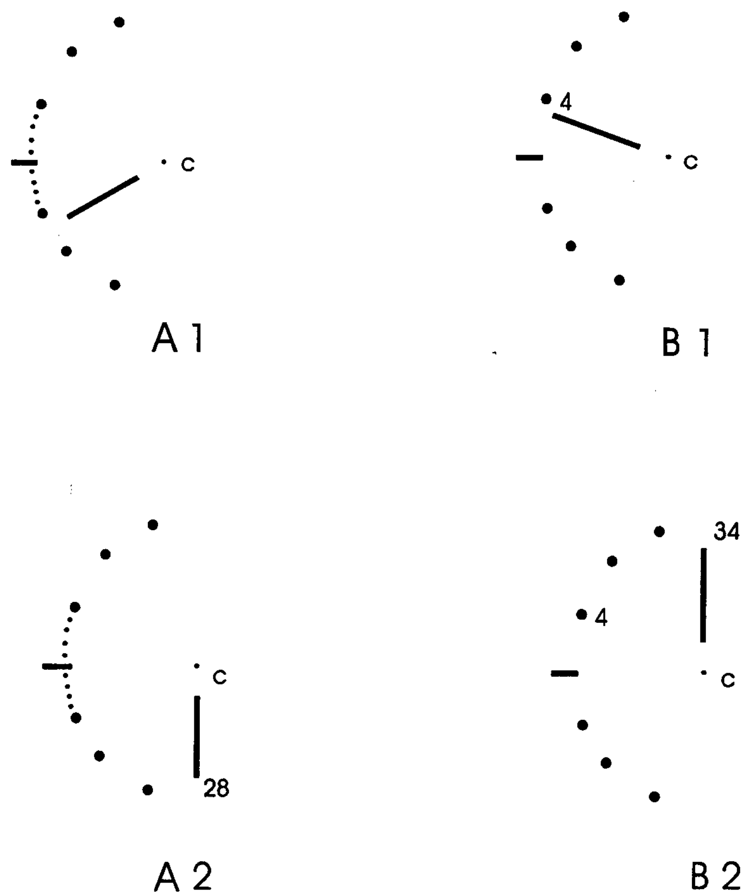


Fig. 14. Variants of vertical velocity indication
A — without a counter of current values in band of ±15 m/s, with 1 m/s division in band of ±5 m/s
B — with a counter of current values in operational band
1 — indication in scale values band
2 — indication of values, getting out of scale limits
C — the centre of indicatory index rotation (not displayed on a frame)

When rate parameter is high variometer data is rather advisory — in this regimes control of such characteristics an attitude, angle of attack, g-load and etc. acquires particular significance. Proceeding from the received information two variants of variometer scales are formed and they are produced in fig. 14. A semicircular dial is used in both variants. Zero was marked by horizontal bar; ±5, ± 10, ±15 points — by dots. There is no calibration of dial. In A variant in ±5 m/s band some additional dots are plotted. They form a dial with 1 m/s division. When current rate parameters exceed the limit of ±15 m/s a digital counter appears at the tip of indicatiry index. This counter displays current value, in ± 15 m/s $< V_y < 20$ m/s band with 1 m/s discretness. When value of 20 m/s is achieved the indicatory index occupies vertical position (comes to brace) the counter displays current parameter in 50 m/s $> V_y \geq 20$ m/s band with 5 m/s discretness. When the parameter is $V_y > 50$ m/s —the discretness is 10 m/s.

Variant B differs from variant A because digital rate counter is indicated in whole band of present parameters; there are no additional scale dotrs in ± 5 m/s range.

The display of pitch angles is very significant for spatial orientation support and recovery from complex spatial situations. For HMD and also for HUD, the difficulty of pitch indication is in the necessity to use as few discrete elements as possible and not to have any possibility to use colours for positive and negative pitch indication. Resting on the analysis of HUD indication type of modern Russian aircrews, there have been formed some pitch display types for evaluation of possibility of their use on HMD. Versions in question are presented in fig. 15.

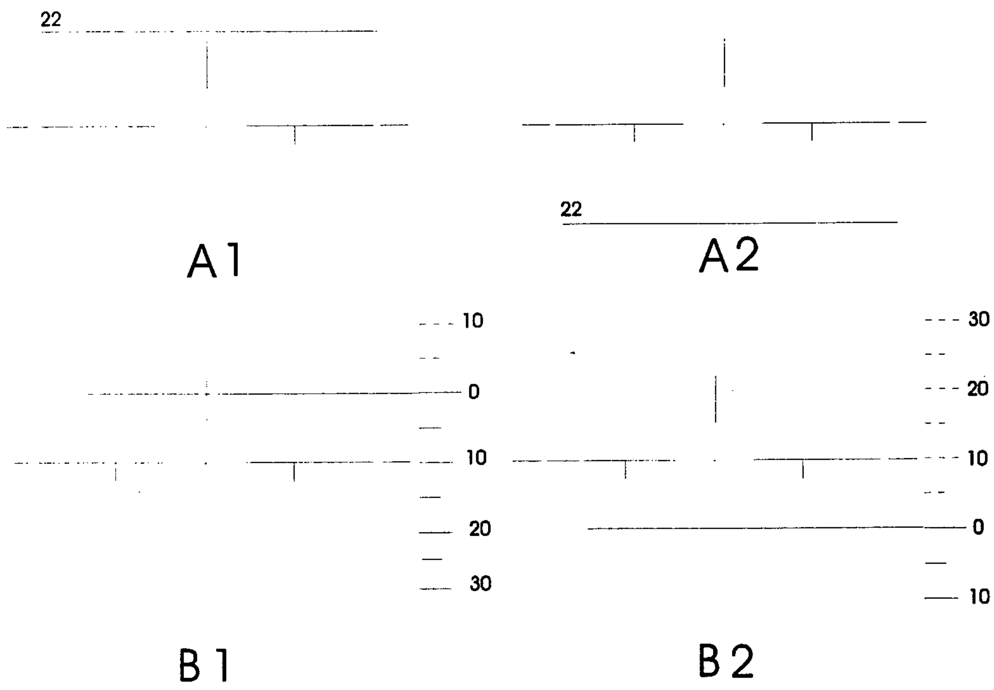


Fig. 15 Pitch indication versions.
A — artificial horizon line with a digital counter.
B — vertical moving scale
1 — negative pitch; 2 — positive pitch

In A variant pitch is displayed as a moving straight line with a digital counter at the tip ofwhich move in a "window" a height of which is ±20°. When these parameters are exceeded the line comes to brace. It means that it doesn't move in a corresponding direction and present pitch parameter is indicated only by the counter. The length of the line is a distance between zero dots of roll scale.

In B version pitch is displayed as a moving vertical scale in "window" ±20°. In a band of pitch positive parameters bars are presentedas a broken line, in negative — as a solid one. Zero pitch is indicated by a straight line Its length from zero mark of pitch scale to the inner end of left zero mark of roll scale.

One of the most actual problems of information encoding on HMD display is searching for effective ways of flight parameter limits indication. An operational practice of modern combat aircrews shows that the cases of going beyond preset limits of angle of attack, g-load and altitude appearing first of all during active maneuvering take place very often.

To provide agile aircrews flight safety present values of angle of attack and g-load should be maintained in a range of allowable values. In most of maneuvers with preset g-load values pilot doesn't need any accurate quantity values of this parameters. So starting with general orientation to minimize symbol-alphanumeric information on HMD screen it is reasonable to ensure quality indication of angle of attack and g-load. This task could be decided with the help of display of special symbol ("staple") which is on a fixed distance from the central point of aircraft symbol and moves relatively this point together with aircraft symbol in proportion with present roll (fig. 16). The position of the "staple" determines top allowable values of angle-of-attack or g-load parameters in priority.

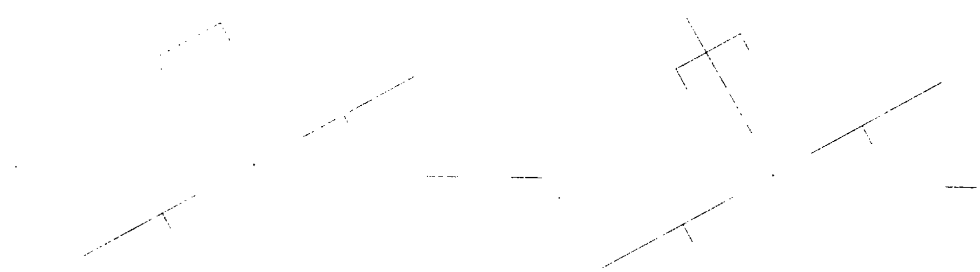
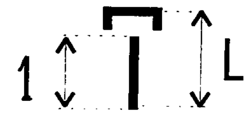


Fig. 16. An allowable limit of angle of attack and g-load parameters display
A — present value is within the range of allowable units
B — angle of attack or g-load value is out of limits.

The length of "fin" of aircraft symbol is proportional to current value of g-load or angle of attack. The length is calculated by the following formula

$$l = \left| \begin{array}{l} 0 \\ \dfrac{\alpha-\alpha_0}{\alpha^{lim}_{max}-\alpha_0}\times L \\ \dfrac{n-n}{n-n}\times L \end{array} \right.$$



$n^{lim}_{y\,max}$ — allowable limit of g-load;

α^{lim}_{max} — allowable limit of angle-of-attack ;

n_y — current value of g-load;

α — current value of angle-of-attack .

Parameters n_o and α_o are determined by characteristics of concrete aircraft. A "fin" braces or pierces the "staple"(fig. 16, B) when angle of attack and g-load values reach their top allowable limits; the "staple" is indicated in a glimmer regime.

The important parameter directly influencing flight safety is altitude. Indication of the parameter on HMD display with the help of traditional circular scales is embarrassing relating to a complexity of frame spatial arrangement. This problem could be decided by using a digital counter for altitude display. The counter provides high accuracy of current values readout, but creates some difficulties in prognozing of indicated parameter change and determination of time stock before getting the critisal altitude.

It's suggested to use two triangular symbols which move from display periphery to its center for indication of time stock when it is possible to recover an aircraft from diving at a minimally allowable attitude with g-load under the limit the moment of of dangerous altitude achievement is indicated by the whole rapprochement of the symbols, making a twinkling cross. This principle of alarming seems to be psychologically grounded because its aim is to switch over pilot's sensor activity from one stereotype to another, direct and organize his actions preventing an achievement of dangerous height.

Altitude alerter appears on the display 5 seconds before getting a critisal height $H^{u}_{оп}$ which accounts time reserve dor turn. The angles draw together in proportion with the time left for getting critical altitude. With getting critisal altitude $H^{u}_{оп} < H^{в}_{оп}$ ($H^{в}_{оп}$ is introduced in mainframe computer) the corners draw together and form a twinkling cross. This flashing stops as soon as an aircraft reach a safe height. The formula of critisal height ($H^{u}_{оп}$) calculation is the following:

when $\lambda < 0$ $\quad H^{u}_{оп} = H^{в}_{оп} + R\,(1 - \cos^{\lambda}) + \tau V_{ист} \sin^{\lambda}$

when $\lambda \geq 0$ $\quad H^{u}_{оп} = H^{в}_{оп}$, where

$H^{в}_{оп}$— a value introduced in mainframe computer; λ —burnout angle;

$\tau = 2$ s;

$$R = \frac{V}{3g}$$

$V_{ист}$ — real current speed

There was hold an analysis of peculiarities of flying parameters display. It allows to form an informational frame HMD (fig. 17) ensuring maximum visual abilities to find and recognize external space, this is gained by the use of minimum number of symbol-alphanumeric elements. Though the question of effectiveness of the frame use for flyer's spatial orientation providing and aircraft's recovery to level flight in complex spatial positions requires further experimental development.

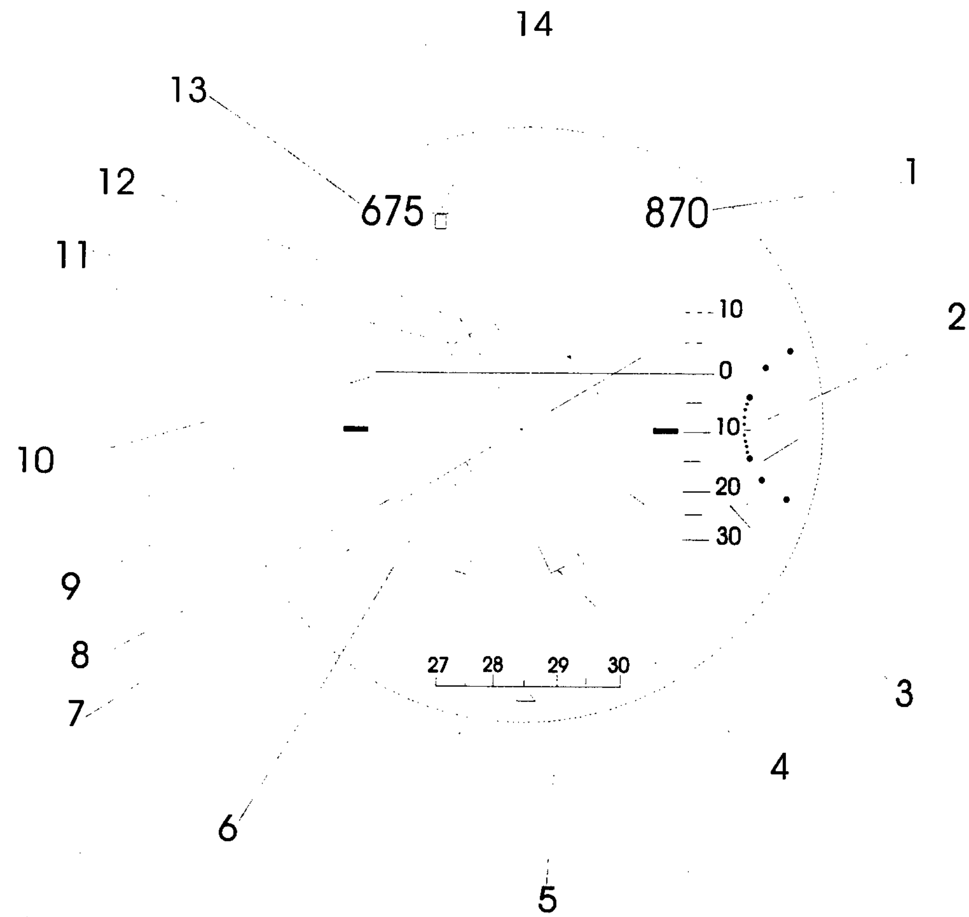


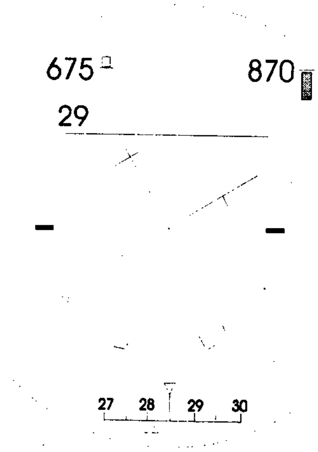
Fig. 17. A version of informational frame HMD for steering with an intensive out-of-cabin orientation

1 — a counter of current altitude;
2 — variometer;
3 — pitch scale;
4 — indices of roll angles limiting;
5 — heading scale (indicator)
6 — aircraft's symbol;
7 — altitude alerter;
8 — roll 30 °
9 — zero roll bar
10 — zero pitch bar
11 — limits of attack angle land g-load
12 — moving "fin"
13. — a counter of current speed
14. — tendency of speed change

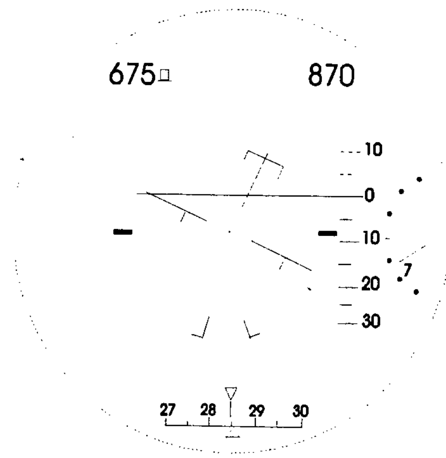
5. Experimental Evaluation of HMD Informational Frames Use Efficiency for Aircraft's Complex Spatial Attitudes Identification and Recovery

Experimental evaluation of HMD informational frames was conducted on interactive-modeling complex (IMC) on the basis of local net personal computers. IMC contains software for dynamic performance simulation navigation model, applied statistic processing programs. IMC devices include control aids (power lever, stike, pedals) displays presenting informational frames and outside scene, pilot's psychophysiological characteristics validation aids. Informational frames were represented by means of an experimental monocular HMD model. The flyer combined HMD informational frame with the displayed external scene. Informational frame image was uncollimated; its surface coincided with the surface of the display where outside situation was indicated. There were tested 3 versions of HMD informational frames, which were formed on the base of test-analytical estimation, stated in the previous parts, and pilot's expert evaluation.

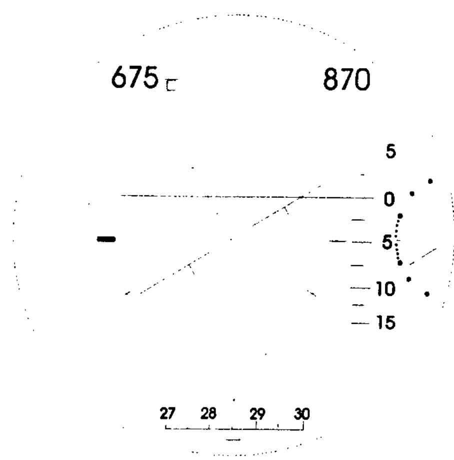
Flight personnel considered the efficient roll pitch and rate indication to be most significant for an identification of aircraft's complex spatial attitudes. Their opinion about the way of roll display was unanimous. A reversal indication is preferable. So this question wasn't subjected to an additional experimental examination. The formed HMD frames were different in presentation way and scale of pitch dial and also in the form of rate data display. The shape of informational frames you may see in fig. 18.



Variant 1



Variant 2



Variant 3

Fig 18. The shape of informational frames formed for test estimation

The description of informational frames versions is represented in table 11.

Table 11

The versions of informational frames formed for experimental validation

Frame number	Pitch presentation form	Rate presentation form
1	Horizontal line with a digital counter on the left moves in the "window" ±20°. When pitch values are over ±20° , it braces and pitch is displayed only by the counter	The symbol of altitude change tendency, in a shape of a small flag of variable dimensions, surrounded with triple line. It is on the right side of the current air speed counter. The flag grows up when it reduces. Maximum size is gained when H ≥30 m/s
2	Vertical scale moving in the "window" ±20°. It is on the left of aircraft symbol . The division is 5°, calibration of values, multiple 10°.	Semicircular scale with ±15 m/s band and digital counter at the tip of the needle. The counter discreteness in the scale range is 1 m/s
3	Vertical scale moving in the "window"±10°. It is on the right of aircraft symbol. The division is 2,5° calibration of values, multiple 5°.	Semicircular scale with ±15 m/s band. In ±5 m/s band the scale has 1 m/s division. The counter is indicated with values ≥±15 m/s.

The comparative investigation was carried out in three stages. At the first stage the pilots handled aircraft in "night" conditions (without visual scene) with a successive use of each HMD informational frame version. At the stage in question each flyer arbitrary chose handling regime. The purpose was to get acquainted with the peculiarities of display of every informational frame version. At the second stage the flyer conducted level flight maintaining during 15 minutes and maneuvers . Maintaining the level flight was carried out with the following settings: altitude — 600 m, speed — 600 m/h, pitch — 0°, roll — 0°, heading — 0°. The maneuvers were executed after finishing level flight. The preset values of flight parameters are represented in table 12.

Table 12

Preset flight parameters at maneuvering

Parameter	Altitude, m		Velocity, km/h		Pitch,deg	Roll, deg	Heading deg
	entry	recovery	entry	recovery			
pull up maneuver	600	3000	900	600	+45*	0	0
dive	3000	600	600	900	–45*	0	0
ascending spiral	600	3000	600	600	—	30	—
descending spiral	3000	600	6000	600	—	30	—

Pilot work load during process of aircraft handling was determined by the test "attention reserves". The essence of the test consists in the following. In front of the pilot there is an illuminated indicator panel with red, green and yellow lamps. Working with this indicator panel is possible only with gaze shift from HMD screen. The pilot should switch off the lamps according to their colour, pushing corresponding button, which were on power lever. The pilot turned to the additional task only in the moment when he could shift his gaze from HMD screen without detriment to quantity of steering. Total number and number of erroneous answers was estimated.

Psychophysiological intensity level during the task fulfillment was validated by values of heart rate. At the third stage aircraft's complex spatial attitudes were simulated. The procedure is the following. The pilot's hands are on aircraft's controls. HMD visual field is combined with the display screen center. There is no visualization of outside

* For a set stage of dive and pitching

situation. In 2-3 s after the preliminary command in HMD screen a frame with a complex aircraft's spatial altitude was performed. Appraising the situation the pilot was to recover aircraft to level flight. There were registered latent period of the first control action, the correctness of the first control action direction and time of recovery to level flight. The performance of complex spatial attitudes are presented in table 13.

Table 13

Characteristics of complex spatial attitudes

Complex attitude number Parameter	1	2	3	4	5	6	7	8
Pitch, deg	−10	+20	−25	+45	+35	+15	−60	−60
Roll, deg	+60	−225	−195	+45	+180	−225	+90	−90
Attitude, m	200	800	1700	1600	250	250	800	800
Rate, m/s	−10	+5	−20	+15	−5	−5	−15	−15
Instrument speed, km/h	800	950	1200	700	400	390	510	510

Complex situations were represented in accidental order. 40 complex attitudes (8×5) were shown to every flyer.After each series of experiments the pilot appraised every version of informational frame by five-mark scale (5-exellent). When all the work had been finished each pilot in a free form stated his comments and suggestions in writing.Sixteen* pilots took part in the investigation.

The results of experimental validation

An acquaintance with the test frames didn't cause any difficulties in flight personnel as there was continuity in the form of data presentation with the existing instruments. The pilots needed to fly aircraft for 30-40 minutes to master the peculiarities of stand dynamics, work with aircraft slight controls.

* For a set stage of dive and pitching

After an acquaintance steering and pilot's ready report he conducted the level flight modeling route flight in hand mode. The characteristics of horizontal flight execution using various HMD informational frames versions are shown in table 14.

Table 14.

The performance of level flight fulfillment using different versions of HMD informational frames ($|\bar{X}| \pm m$)

Parame-ters	Deflection from present values					Heart rate pulse beat/min	Attention reserves*
Version	altitude, m	velocity, m/h	pitch, deg	roll,deg	heading, deg		
1	4,2±1,1	4,9±1,5	1,5±0,8	2,9±1,2	0,9±0,3	77,3±4,6	38±12(2)
2	3,9±1,2	3,7±1,3	2,9±1,2	2,4±1,1	78,2±3,8	78,2±3,8	3414 (1)
3	3,9±1,2	4,8±1,2	1,4±0,7	2,8±1,3	75,3±4,7	75,3±4,7	39±11(1)

The data of table 14 show that all the tested versions of HMD frames at level flight stage ensure high enough flying accuracy with practically equal levels of psychophysiological intensity and pilot's attention reserves. On executing maneuveres another picture took place. There are valid differences in accuracy of preset flight parameters maintaining between the first and the second, the first and the third versions. The main distinctions in the compared modes of informational frames are found out in the vertical control axis. The accuracy of holding preset recovery altitude using indication version 1 during executing such figures as "vertical climb" and "dive" is 29% lower in comparance with versions 2 and 3 by exactness of pitch maintaining the differences reached 40%. The accuracy of maintaining of such parameters as velocity, roll, heading were practically similar when using any HMD informational frames versions. The attention reserve levels with the first, the second and the third versions reliably varied ($p<0,01$); the value of this difference attained 30-40%. Psychophysiological intensity levels with various HMD informational frame versions differed only during fulfillment maneuvers "vertical climb" and "dive". The value of these distinctions was 8-10%, but didn't reach statistically significant reliability level. So, as the experimental studies show the form of data display in HMD screen influence the accuracy performance of steering, the level of psychophysiological load and intensity. In the first indication version control difficulties in vertical axis are related to lack of pitch and rate representation. Digital counters are used to display this parameters in the version in question. It is hard to prognoze a change of this parameters with the help of this counters. Besides this the line of zero pitch moves within the limited angle band because of HMD screen working field dimensions. With current pitch values more than ±20° the cursor stops at the extreme up or down position. This may cause errors in determination of pitch values.

* Total number of answers (number of errors) per 1 minute of working

Table 15

The performance of maneuvers fulfillment with the use of various versions of HMD informational frames ($|\bar{X}| \pm m$)

Maneuver / Parameter	Vertical climb			Dive			Ascending spiral			Descending spiral		
	Version			Version			Version			Version		
	1	2	3	1	2	3	1	2	3	1	2	3
Altitude, m	67±24	51±17	52±11	53±14	41±14	42±11	18±5	16±7	15±5	17±4	15±7	15±5
Velocity, km/h	24±8	23±5	25±4	17±5	19±6	18±5	14±3	13±4	15±4	15±4	14±3	16±5
Pitch, deg	4,7±4,1	3,2±2,1	2,9±2,4	4,6±4,0	2,8±1,6	2,9±1,5	—	—	—	—	—	—
Roll, deg	2,2±1,2	1,8±0,9	1,9±0,9	1,8±1,2	1,8±0,9	1,9±0,8	1,2±0,2	1,3±0,2	1,2±0,3	1,3±0,4	1,2±0,1	15±0
Heading, deg	3.1±1,1	2,8±0,8	3,1±0,9	2,1±1,1	2,7±0,8	2,2±0,8	—	—	—	—	—	—
Attention reserves*	12±5 (2)	21±6 (2)	19±5 (1)	11±5 (1)	22±5 (2)	21±4 (0)	13±4 (0)	23±6 (1)	20±5 (1)	15±3 (0)	22±5 (0)	21±4
Heart rate, pulse beat/min	86±6	79±5	80±6	87±5	79±6	81±6	78±5	79±6	78±6	77±4	77±6	78±5

* total number of answers (total number of mistakes) per 1 minute of working

At the third stage of investigations there were studied the characteristic features of pilot's activity when the versions of informational frames were used to recover the aircraft from complex spatial attitude. The use of "complex spatial attitudes" methods allows to compare quantitatively pilot's spatial orientation reliability in various conditions.

The results of this test execution with HMD indication modes are represented in tables 16, 17.

Table 16

Probability and duration of the first erroneous control action in the longitudinal and lateral aircraft control axes when HMD informational frame modes are used

Factor	Display version					
	longitudinal axis			lateral axis		
	1	2	3	1	2	3
Probability of erroneous action	0,033	0,021	0,017	0,008	0,013	0,008
Period of erroneous action execution, s	1,28	0,98	1,03	1,07	1,02	0,97

Table 17

Latent period of the first correct control action and time of aircraft's recovery from complex spatial attitudes when various versions of HMD informational frame are used

Factor	Display version		
	1	2	3
Latent period, s	1,64±0,12	1,26±0,06	1,27±0,04
Recovery time, s	13,6±0,41	11,4±0,31	12,5±0,29

As it may be seen from the represented data the performance of aircraft recovery from complex spatial attitude with the second and the third versions of informational frames differ only in time of recovery from a complex situation. The use of the first version provided worse conditions for pilot's spatial orientation in cases when aircraft's complex spatial attitudes arise. That was displayed by the greater probability of erroneous control actions in longitudinal control channel, greater duration of period of aircraft's recovery to level flight. In comparison with the second mode the difference reached 2,2 s. The distinctions in question have high degree of statistic reliability ($p<0,01$). According to flyer's estimation such period might have decisive significance for flight safety providing during aircraft's recovery from complex spatial attitudes.

During the analysis of data of subjective evaluation of HMD informational frame modes which differ in pitch and rate representation form the following results were got:

1) The majority of the pilots pointed out the inconvenience of using a moving line with a counter (version 1) as an indicator of pitch angles because of arising difficulties in spatial attitude and angular pitching speed determination with high values of pitch angles, when the line comes to "brace".

The mode of pitch scale (version 2) is considered to be the most successful as the pilots don't have any doubts in aircraft's spatial attitude identification when reading the values of this scale.

2) Practically all flyers stated that calibration of variometer at the pointer tip (version 2) isn't necessary and considered that running figures distract their attention and prevent the pitch scale reading at the level of its calibration. One of the flyers took note of the necessity to identify thedigital data at the tip of variometer pointer during aircraft's approach

to land. The majority of the pilots agreed that the variometer in the second mode is sufficient for normal flying the aircraft. The results of subjective HMD informational frame evaluation in five mark scale are presented in table 18.

Table 18

Average values of subjective estimation of work convenience when various HMD informational frame modes are used

Informational frame mode	Mark validation
1	3,50±0,71
2	4,45±0,06
3	3,75±0,35

As it may be seen from the represented data the first display version got the minimum mark. The highest mark has the second indication mode. We should note that on its validation the opinion of the flight personnel was the most unanimous. The minimum deflection from an average value mark reveals this.So the test estimation results show that the suggested HMD informational frame layout and data capacity ensure the sufficient enough flyer's spatial orientation and the necessary flying accuracy during executing basic maneuvers and aircraft's recovery from complex spatial attitudes. In the examined versions the most preferable pitch display mode is a movable scale with 5° division and calibration through ±10°. For vertical speed — semicircular scale with ±15 m/s band and a division from 0 to ±5 — 1 m/s, then — 5 m/s. The reference index is executed in the form of a thin line. The quantity value of the parameter out of the scale range is presented with a digital counter. At the tip of the reference bar which is bracing at the scale edge 1 m/s division distant. The bars corresponding to ±5, ±10, ±15 m/s are at 25°,50°, 75° angles accordingly. The suggested mode of informational frame is represented in fig.19.

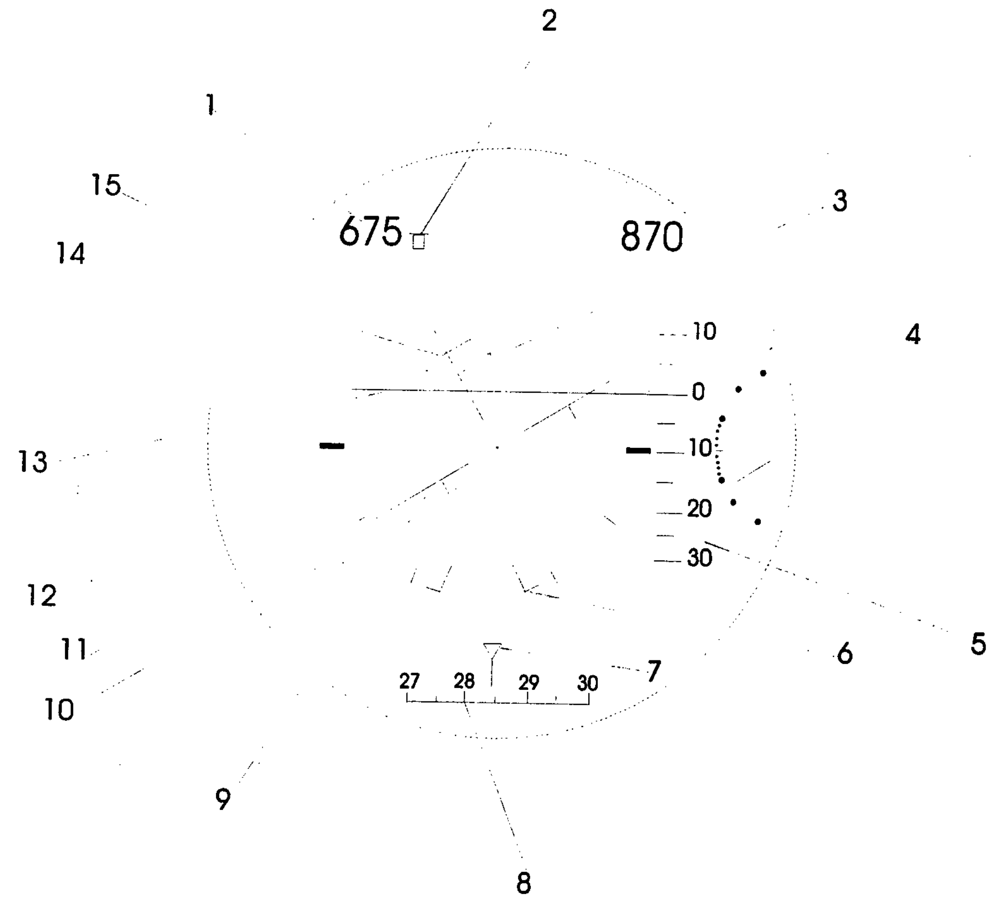


Fig. 19. HMD informational version for target indication regime
1 — current velocity counter
2 — velocity change tendency
3 — current altitude counter
4 — variometer
5 — pitch scale
6 — index of roll limitation
7 — reference index of present heading
8 — heading scale
9 — aircraft symbol
10 — attitude alerter
11 — 30° bar of roll scale
12 — 0° bar of roll scale
13 — zero line of pitch scale
14 — index of angle-of attack an d g-load limiters
15 — moving "fin"

The recommended informational frame was formed according to the statement about the necessity to ensure optimal conditions for out-of-cabin space observation. Relating to this the frame contains information necessary for flying in VFR conditions, with constant ground surface and natural horizon line visibility.

For conducting complex maneuvers, approach mode providing, flying a preset route and etc., an additional quantitative data, which can be entered to in HMD informational frame, is required. This will naturally deteriorate the conditions of external space visualization and will lead to the use of square reserve on the right edge of the frame, meant for additional data indications at the stages of target indication. So, from our viewpoint it is reasonable to use two main versions of informational frames in HMD: flight frame, containing full data amount and a frame for target marking, containing the minimum necessary flight capacity and space reverses for additional data display.

Taking all the foresaid into consideration HMD pilotage informational frame was formed. It is represented in fig. 20.

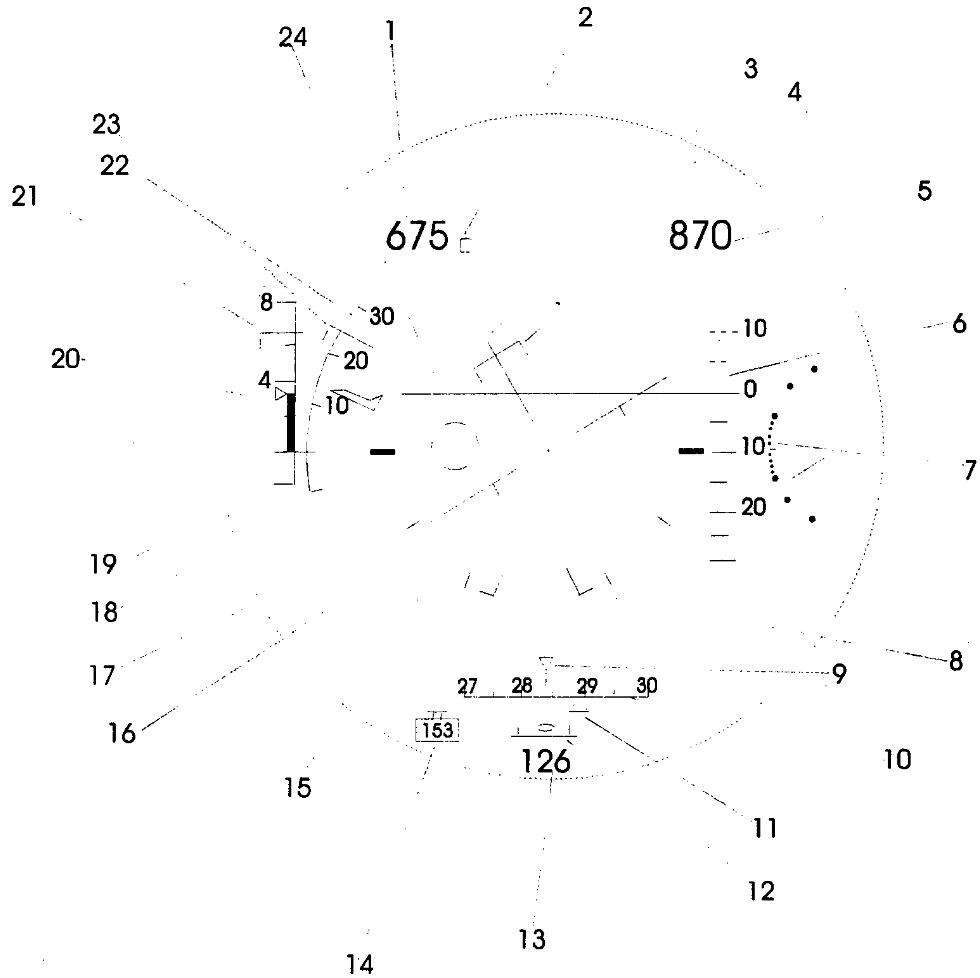


Fig. 20. HMD pilotage informational frame

1 — present speed counter
2 — speed change tendency
3 — moving "fin"
4 — AOA/G limiter
5 — present velocity counter
6 — pitch scale
7 — variometer
8. — index of roll limitation
9 — reference index of present heading
10 — heading scale
11 — set heading
12 — sideslip indicator
13 —range from navaid point
14 — set heading counter
15 — aircraft symbol

16 — altitude alerter
17 — 30° bar of roll scale
18 — 0° bar of roll scale
19 — zero line of pitch scale
20 — G-load scale
21 — G-load limit index
22 — angle-of attack indicator
23 — angle-of-attack limitation index
24 — index of director control

The following parameters are presented in HMD flight frame in addition:

— the value of preset course (11) is indicated by a moving triangle in ±30° range under the heading scale. When the difference between preset and current heading is over 30° the triangle comes out of the scale bounds and stops at a distance of 5° on side where the reading from the preset value to current is less than 180°. Together with this there appears the current heading counter (14) under the pointer in the frame;

— the slideslip indicator (12) is linear, vertical bars correspond to permissible slide values. A reference index in the form of a "ball". The indicator twinkles when slide value reaches its limit;

— the range from navaid point (13) — digital counter. The range is displayed in a bee-line up to the next navaid point;

— vertical g-load (N_y) — vertical scale (20) with 2-unit division and 4-8-unit calibration. Scale range from -2 to 8 units. A reference cursor in the form of semibrace (21), which twinkles on reaching a bound value;

— angle of attack scale in the form of arc (22) with the band from

-10° to 30° in the form of triangle, calibration at (near) the bars 10°, 20° and 30°. A reference index in the form of a stylized aircraft symbol. A bound angle-of-attack value is displayed by semibrace (23) in the scale. On reaching a limit value the brace twinkles;

— the index of director control — circle, with the diameter equal to the distance between the ends of winds of aircraft symbol.

6. THE INFERENCE

On the basis of the pilot's inflight spatial orientation tests and the analysis of the experience of electronic indication application to modern aircrews there were formed two versions of HMD informational frames (fig. 19, 20). The evolutionary approach was taken as a principle of informational frame development. This method suggests maximum preservation of sensor, motor skills and experiences which flight personnel has. This is gained by the maintaining of habitual spatial layout of the main elements of informational field such as capacity, form and logic of flight data presentation. A preliminary experimental estimation on an interactive-modeling complex showed high enough flying accuracy and spatial orientation reliability during aircraft's recovery from complex spatial attitudes.

In accordance with the contract in the materials of the next stage it is intended to test the ability of HMD usage for pilot's inflight spatial orientation providing at steering a simulator modeling typical flight tasks.

REFERENCES

1. Anisimov G.V., Lapa V.V., Saphronov A.M. Eye movements recording as a method of engineering-psychological investigations. — M.: Mashinostroyenie, 1985. — 96 p.

2. Berezkin B.S., Zinchenko V.P. The study of informational search / Problems of engineering psychology. — M.: Nayka, 1967.

3. Borisov et all. A reference book on engineering psychology. — M.:Mashinostroyenie, 1982. — P. 129-149.

4. Borodin V.P., Rylsky G.U. Flight complexes and systems of plane and helicopter control. — M: Mashinostroyenie, 1978. — 216 p.

5. Browne R.C. Figure and ground in a two-dimentional display // J. Of Applaied psychology. — 1954. — Vol. 38, № 2. — P. 462-467.

6. Dushkov B. A. et all. The foundations of engineering psychology. — M.: Vishaya Shkola, 1977. — C. 137-161.

7. Hasbrook A.H., Rasmussen P.G. In-flight performance of civilian pilots using moving-aircraft and moving horizon attitude indicator // Federal aviat. Administr. Office Av. Med. Civil Aeromed. Inst. Oklahoma City, Rept. FAA-AM-73-9. 1973.

8. Johnson S.L., Roscoe S.N. What moves, the airplane or the world? // Human factors. — 1972. — Vol. 14, № 2. — P. 107-113.

9. Kovalenko P.A. Spatial orientation of pilot. — M.: Transportation Publ, 1989. — 230 p.

10. Kopanev V.I. What demonstrated experiment? // Aviation and cosmonautics. — 1997. — № 3. — P. 12.

11. Kotik M.A. Engineering psychology course. — Tallinn: Valgus, 1978. — P. 238-250.

12. Krylov A.A., Yusupuv I.M. Toward effect of subjective spatial image of efficiency of operator's performance // Problems of engineering psychology and ergonomics. — Yaroslavl, 1974, first ed. — P. 168-178.

13. Lapa V.V., Lemeschenko N.A. Psychophysiological optimization of informational interaction in "pilot-aircraft" system // Aviation and space medicine, psychology and ergonomics. — M.: Polyot, 1995. — P. 186-193.